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To cite this article: I. Smolyanov *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **950** 012026

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Numerical calculation of large-sized objects induction heating

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Abstract.

The paper describes a numerical procedure for modeling induction heating of large objects. A coupled calculation of the electromagnetic and thermal fields is performed by the finite element method in a three-dimensional formulation. The setting of the computational mesh is described. The results of numerical calculations are demonstrated.

1. Introduction

In many industrial processes, there is a need for uniform heating. For example, during the hot stamping light-alloy parts for the aircraft industry, it is necessary to preheat the stamping tool [1]. This tool is a steel part weighing 10-20 tons. Previously, this problem was solved by simple heating in resistance furnaces. However, this method takes a very long time and is accompanied by large heat losses.

It was proposed to use induction heating for this technological operation [2, 3]. Induction heating, compared to resistance heating, is characterized by a high heating rate and efficiency, since energy is released directly into the object [4].

The uniformity of heating in this case can be achieved by selecting the inductor geometry and the power supply parameters (power, frequency). Coupled electromagnetic and thermal analysis for the selection of these parameters is performed either analytically or numerically. However, induction heating provokes the skin effect. This effect is described by the fact that the electromagnetic field and Joule heat realizing are concentrated in a surface layer called the penetration depth. In the case of heating large-sized objects, the scale of the object and the depth of penetration can differ dramatically [5, 6] and can be a problem for numerical calculations. This work describes the features of the numerical procedure for calculating induction heating of large scale objects.

2. Experimental setup

Considering installation is shown in the Fig 1. The unit consist of the stamp tool (orange color), the steel plate (magnet color) and the base plate (light green color). The general part of the unit is the stamp tool. Temperature of the part should be acquired up to 450-550 degree Celsius, depending on the type of heated product, and maintained to the value during whole working day (about 21600 second). Particularly important is the upper part of the die, as it is in contact with the workpiece. It can be finded more information in works [2]. To maintain the set temperature



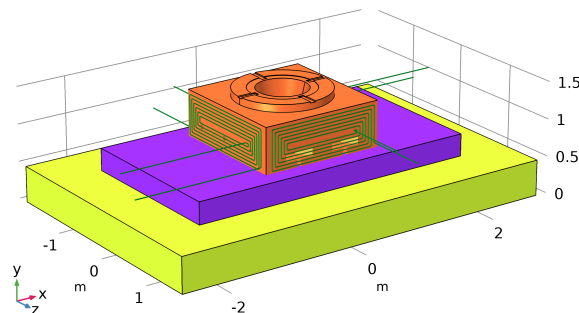


Figure 1. Geometry of stamp induction heating installation

level, induction heating is carried out using four inductors (dark green color) on each side of the stamping tool. The maximum power for each pair of inductors is 30 kW and depends on the source.

The inductor is a specially shaped water-cooled coil made of copper tube (electrical conductivity $6e7$ S/m). The steel (magnet) and base (light green) plate and stamp tool (orange) made of difference kind of steel, but it can be neglected because of weak influence on temperature field. The properties of the parts have following values, the specific heat capacity is 440 J/(kg·K), the mass density is 7870 kg/m³, the thermal conductivity is 76.2 W/(k·m), the electrical conductivity is $6.25e6$ S/m. The thermal insulation maded of kaolin is set between stamp tool (orange) and coils (dark green). The properties of the insulation following: thermal conductivity is 0.13 W/(K·m), the mass density is 300 kg/m³, the specific heat capacity is 1000 and the thickness of the insulation is 20 mm.

3. Numerical model

The problem is multiphysics and have difference values of time derivativeties for each task. The term task here means the solution of the field equation in partial derivatives. The problem consist of magnetic and temperature fields. The magnetic field serves for to produce energy suggested for transforming to heat. The field changes its value over time, but the size of calculating domains is much less than wavelength of the field. Therefore, the equation (1) can be rewritten as (2). This approach will make it possible to rationally use the computing resources of a computer, since the estimated heating time is about 21600 seconds, and the frequency of the magnetic field is about 10 kHz. For the correct resolution of this equation, assuming that the source of the magnetic field changes according to the harmonic law in time, it will be necessary to recalculate the equation at least 10 times per period. From this it follows that the minimum step of the magnetic field equation solver is 10 μ sec. This makes it practically impossible to use the dynamic equations of the magnetic field. Therefore, it is advisable to use in this study the harmonic equation of the magnetic field, where the time derivative is replaced with the help of the complex Laplace term.

$$\text{curl} \left(\frac{1}{\mu} \text{curl} \mathbf{A} \right) + \gamma \left(\frac{\partial \mathbf{A}}{\partial t} - \mathbf{v} \times \text{curl} \mathbf{A} \right) = \mathbf{J}_{\text{ext}} \quad (1)$$

$$\text{curl} (\text{curl} \mathbf{A}) = j\mu\omega\gamma \mathbf{A} = \mu \mathbf{J}_{\text{ext}} \quad (2)$$

Here, μ denotes the magnetic permability, γ is the electric conductivity, \mathbf{v} is the vector of velocity, \mathbf{J}_{ext} represents the current density, $\mathbf{A} = \text{rot} \mathbf{B}$ is the vector magnetic potential.

The temperature distribution is calculated only in the area of the instrument. Heat removal to the environment is modeled using the heat transfer coefficients obtained experimentally. The temperature field in the heated stamp tool due to magnetic field is described by the heat transfer equation in the general form

$$\operatorname{div}(\lambda \operatorname{grad} T) = \rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \operatorname{grad} T \right) - w \quad (3)$$

Here, (λ denotes the thermal conductivity, ρ denotes the mass density, c_p is the specific heat at constant pressure and w stands the volumetric internal sources of heat in the stamp tool. The volumetric heat sources w are represented by Joule losses w_j and losses arising from the phenomenon of hysteresis w_h . The latter of them can be neglected in this study because of their insignificant significance. Joule heat can be calculated using the well-known formula

$$w_j = \frac{|\mathbf{J}_{\text{ind}}|^2}{\gamma}, \text{ where } \mathbf{J}_{\text{ind}} = j \cdot \omega \gamma \mathbf{A} \quad (4)$$

Here the induced current density is defined as \mathbf{J}_{ind} . The Joule heat is determined based on calculations obtained in a magnetic field and comparing them with experiment. It should be noted that the investigated magnetic field is not inert with respect to the temperature field, in other words, changes in the temperature distribution in the investigated region do not play a significant role in the values of the magnetic field. Therefore, in this study, the magnetic problem is calculated once from which the calculation of the thermal energy arising in the heated part is made. This value is considered the maximum value of the heat energy released in the load. During the calculation, the value of thermal energy in the die tool is varied using a non-linear coefficient, which depends on the temperature of the workpiece at a certain point and the maximum temperature in the workpiece. This control mechanism is similar to the principle of energy control with a P-controller. All these equations are solved using the finite element method in a three-dimensional formulation in the Comsol Multiphysics numerical package.

One of the most difficult tasks in solving this problem is the correct grid setup. The dimensions of the structure are meters, and the penetration depth of the magnetic field is millimeters. This disproportion should be solved in an optimal way, so that the accuracy of the calculations corresponded to the engineering concept, and the computing power was acceptable for an average computer. In part, this was solved in this work, the basic representation of the grid is shown in the figures 2 and 3. For clarity of representation of the computational grid, the studied regions of the inductor and air were suppressed in Figure 2. The inductor mesh is shown separately in Figure 3.

4. Results

The main goal of this work is to conduct a preliminary evaluation of the main physical phenomena occurring in this installation, which affect the efficiency of the die press. Also evaluate the correctness of the used mathematical models and assumptions for the analysis of the results. One of the first points for research is the influence of the dimensions of the installation, how to take them into account correctly, as well as the construction heterogeneity on the distribution of the temperature and magnetic fields.

In the process of designing an installation for heating a die tool, more than 20 types of inductor were considered, some of them are considered in [2, 3]. In this work, one of them was chosen at random to assess the distribution of fields in zones with complex geometry. To do this, we plot the distribution of magnetic induction on the surfaces of the installation (Figure 4). It should be especially noted that almost the entire field is concentrated in the area opposite the inductor. This leads to the fact that the central part of the stamping tool has a significant

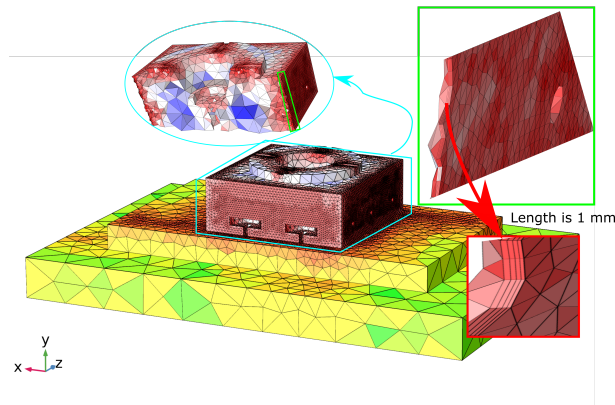


Figure 2. The computational mesh of the stamp installation.

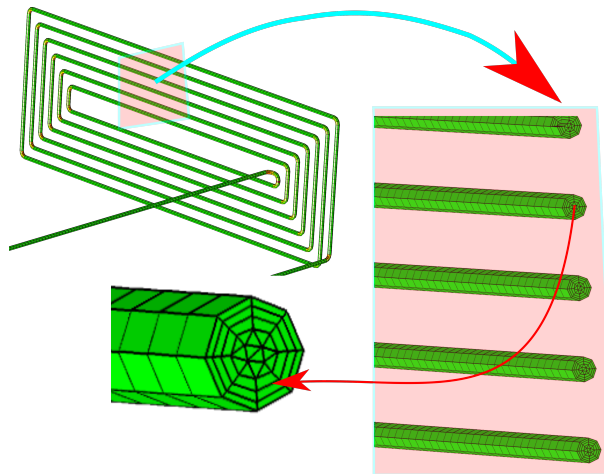


Figure 3. Numerical mesh of one of four inductors

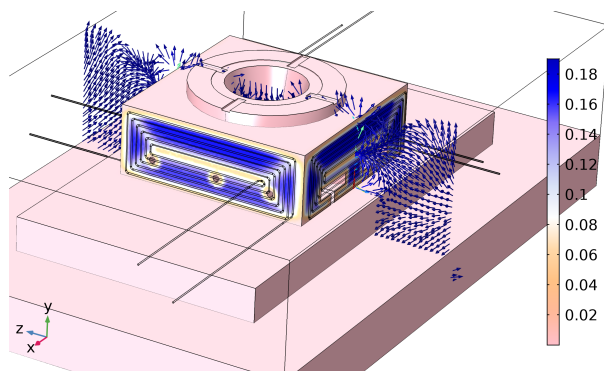


Figure 4. Normal Magnetic Flux Density on the surfaces of the unit

subsidence in relation to the value of the magnetic induction. Also, this phenomenon can be observed in places with uneven geometry (notches and gaps).

Therefore, it is worth evaluating the distribution profile of the released heat power in the die tool (Figure 5). Lowest heat dissipation in areas with low induction. These designs help to

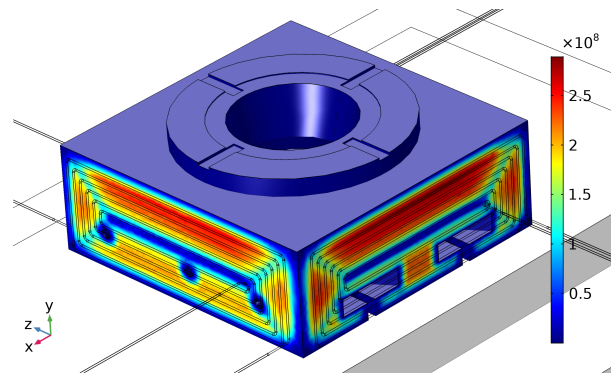


Figure 5. Volumetric Joule heat power, W/m^3 loss density

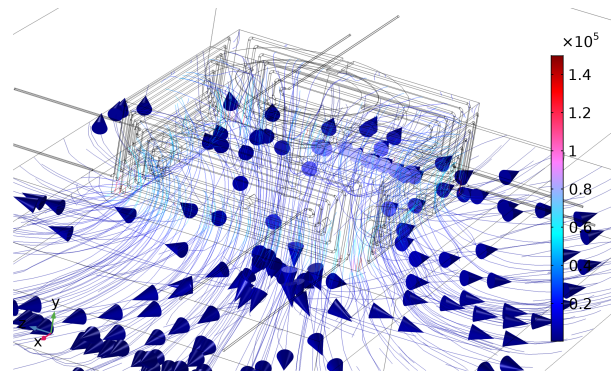


Figure 6. Streamlines of heat flow through the study area

optimize and redesign the inductor design to improve the efficiency of the die heating system.

In addition to the effect of the magnetic field on the efficiency of the test facility, the thermal component also makes a significant contribution. Namely, it is necessary to look through which parts of the study area the maximum outflow of thermal energy occurs. This distribution is shown in Figure 6 using color-coded streamlines. It can be seen that the maximum energy outflow occurs at the junction between the die tool and the steel plate, as well as into the plate itself. The temperature gradient is significantly greater between the environment and the punching tool than between the steel plate and the punching tool. This is due to the presence of a layer of kaolin wool between the inductor and the stamping tools, which significantly reduces heat losses through this surface. It should be noted in the future that a layer of thermal insulation can be added at the junction between the stamping tool and the steel plate in the corner part of it, which should lead to an increase in thermal efficiency.

A decrease in efficiency does not always lead to a high-quality implementation of the planned technological process. For example, in this case, the presence of a significant value of the temperature gradient leads to an increase in the phenomenon of heat transfer due to the thermal conductivity of the medium. This allows in some cases to level the uneven distribution of the magnetic field, heat sources due to the complexity of the design and to equalize the temperatures due to the phenomenon of thermal conductivity. This can be seen in the temperature profile in general, and in its various projections (Figure 7)

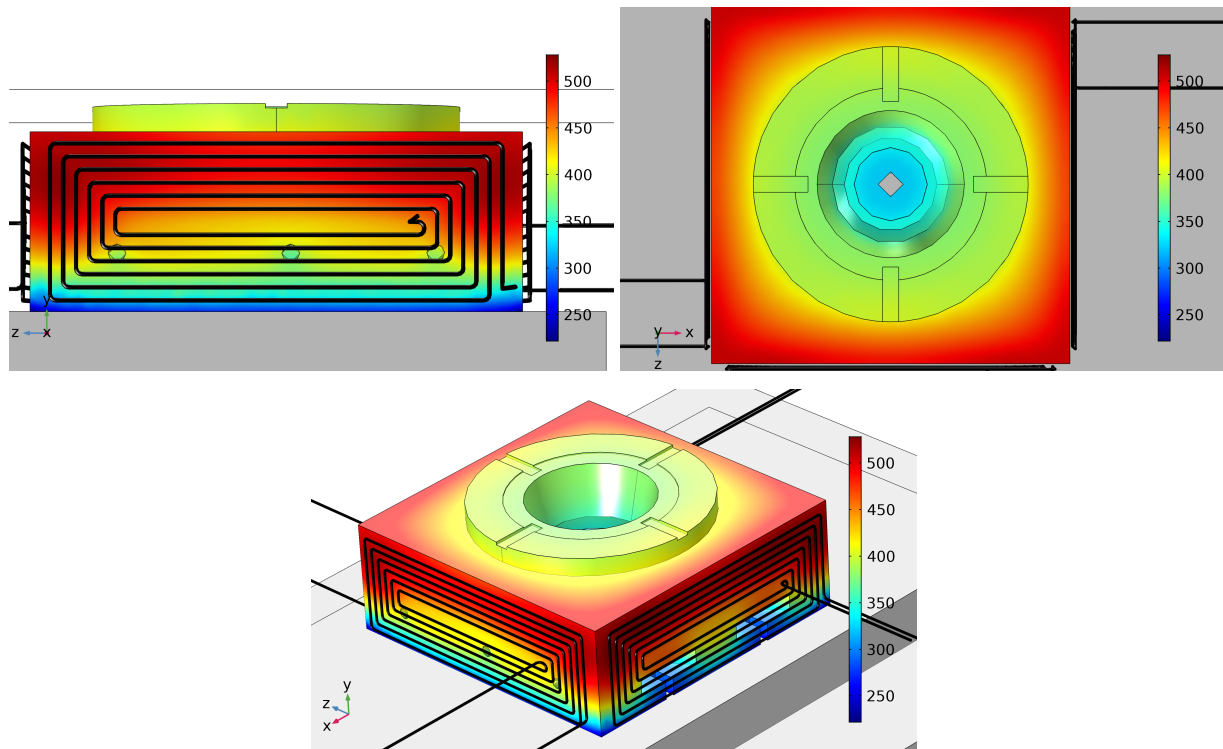


Figure 7. Temperature in the stamping punch

5. Conclusions

In this paper, the basics of modeling large-sized installations using numerical analysis, namely the finite element method, were considered. The main problem solved in this work was to qualitatively evaluate the main features of heating a die tool of large dimensions and complex shape using induction heating. In the work, the main points related to the unevenness of the magnetic field due to the unevenness of the space of the geometry of the die installation and the design of the inductor were considered. The main disadvantages and advantages of this heating approach and plant design were also discussed. Conclusions are drawn about the effect of the temperature gradient on the alignment of the temperature profile in the entire volume of the workpiece. In subsequent works, it is planned to consider systems for controlling the heating of a die tool, design optimization, as well as a number of numerical methods that will reduce the load on computing resources.

Acknowledgments

This work was financially supported by the Ministry of Science and Higher Education of the Russian Federation, project No. 075-11-2019-028.

6. References

- [1] Karbasian H and Tekkaya A 2010 *Journal of Materials Processing Technology* **210** 2103 – 2118 ISSN 0924-0136 URL <http://www.sciencedirect.com/science/article/pii/S092401361000213X>
- [2] Tarasov F E, Marinkova E O, Bychkov S A and Frizen V E 2017 Calculation of inductor for stamp tools heating systems *2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)* pp 1594–1599
- [3] Bychkov S A, Tarasov F E, Frizen V E and Smolyanov I A 2017 Stamp tool induction heating system *2017 18th International Conference on Computational Problems of Electrical Engineering (CPEE)* pp 1–4
- [4] Lupi S, Forzan M and Aliferov A 2015 *Induction and direct resistance heating: Theory and numerical modeling*

- [5] Demidovich V and Perevalov Y 2019 *Metallurgist* **63** 617–626
- [6] Demidovich V and Perevalov Y 2019 *Russian Electrical Engineering* **90** 781–785